PASQAL

PASQAL : QML Progress

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QTML November 2023

PASQAL at a Glance

>20

CLIENTS

Multiple QPUs sold via HPCQS framework, activities in more than 10 countries, and engagements with top cloud distributors

40

YEARS

History in quantum technologies

350+

QUBITS

Best-in-class qubit count and path to 10,000 qubits available in the cloud in 2026

200+

EMPLOYEES

18 nationalities

15+

PATENTS & APPLICATIONS

800+ publications

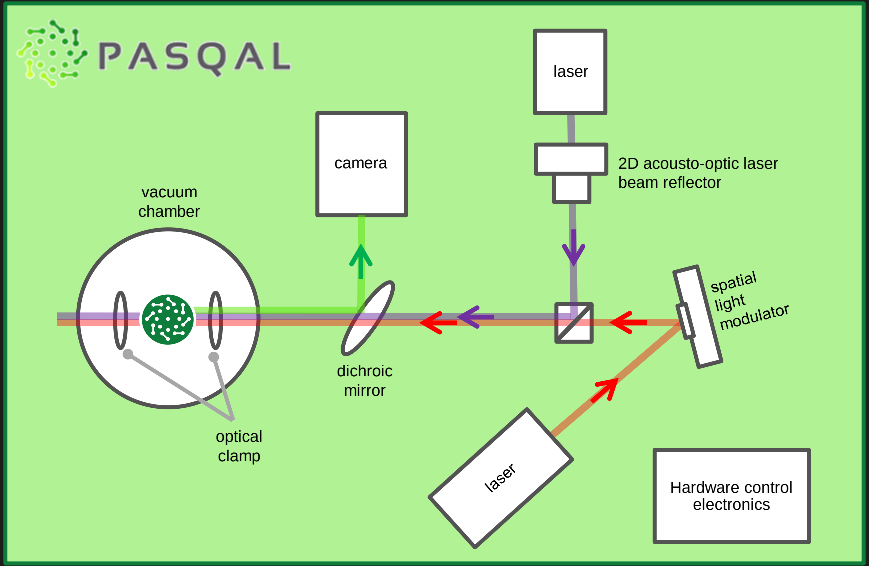
FULL-STACK

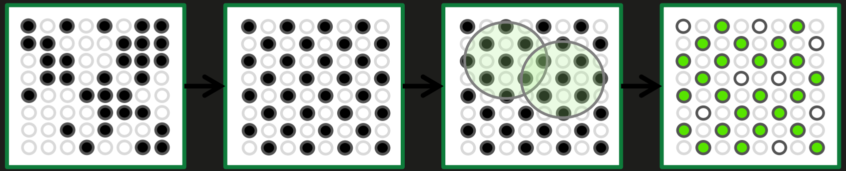
QUANTUM HARDWARE AND SOFTWARE TODAY

Aiming for Practical Quantum Advantage

PASQAL Hardware

PASQAL manufacturers industrialized neutral-atoms type quantum processors offering attractive scaling, flexible topology and analog and digital computational mode





- Currently available systems are in the order of 300+ qubits
- Clear blueprint to showcase 1000 qubits in near-term
- Analog and analog-digital capabilities
- Development of Algorithms and Solutions

Our Full-Stack Solution is Key to Driving Customer Success

PASQAL's comprehensive full-stack offer covers the full range of needs from the quantum computer hardware to the way to use it on personalized software on use cases

Hardware[1]

Gen 1
100 / 200-Q

Gen 2
512 / 1,024-Q

Gen 3
5,000 / 10,000-Q
and beyond

GPU Cluster
Emulator

Offerings

Access	• Cloud access • Data center install • On-premise install
Platform	• Coding platform • GUI • Software integrations
Solutions	• Turnkey solutions per problem and sector • Chemistry, CFD[2], Finance
Libraries	• Quantum (ready) algorithms per mathematical problem • PDE, optimization, ML
Support	• R&D support • Tech support • Maintenance

[1] Q represents qubits
[2] CFD represents computational fluid dynamics

Merger PASQAL <> Qu&Co for application-driven Research

Application-driven in-house quantum algorithm research

In January 2022, PASQAL announced merging with quantum software startup Qu&Co

Accelerating research and the road towards quantum advantage by combining HW technology & problem orientations

PASQAL'S Mission

We want to make the world and industry **quantum-ready**, and develop concrete **quantum solutions** for their most valuable problems.

At the same time, we are eager to research towards **quantum advantage** and the impact it can have to our socio-economic world.

Where do we see quantum advantage in the near future?

Computational Advantage will arise in the design of quantum solutions (and algorithms) for classically hard problems and use cases with relevance to our world.

Use Cases with relevance to the industry and the socio-economic world

Current Technologies

- 300+ Physical Qubits are available
- Fault Tolerance is still a regime to be explored
- Error Mitigation Techniques
- Some sort of advantage can be demonstrated

Quantum Advantage Candidates

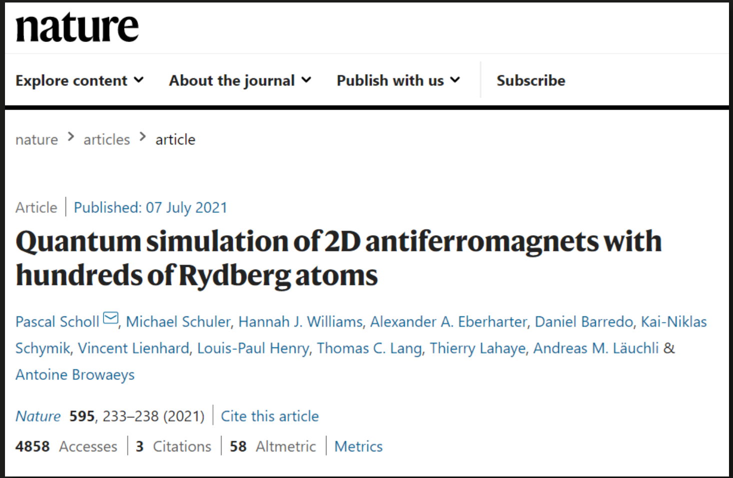
- Classically Hard Problem
- Relevant solution takes too much time if feasible
- Use Case has an impact for our world
- Have a benchmark (at least in smaller scale)

Accuracy and Precision should not be mixed !

We care for both (at least in most cases!)

Application: Quantum Simulation for Scientific discovery

Analog Quantum Simulation are already operating in a regime going beyond the capabilities of classical supercomputers



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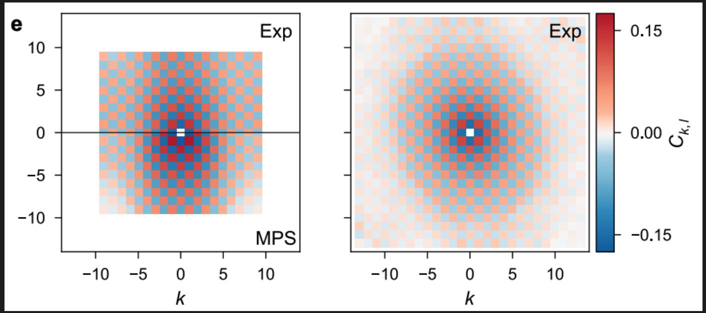
Article | Published: 07 July 2021

Quantum simulation of 2D antiferromagnets with hundreds of Rydberg atoms

Pascal Scholl, Michael Schuler, Hannah J. Williams, Alexander A. Eberharter, Daniel Barredo, Kai-Niklas Schymik, Vincent Lienhard, Louis-Paul Henry, Thomas C. Lang, Thierry Lahaye, Andreas M. Läuchli & Antoine Browaeys

Nature **595**, 233–238 (2021) | Cite this article

4858 Accesses | **3** Citations | **58** Altmetric | Metrics

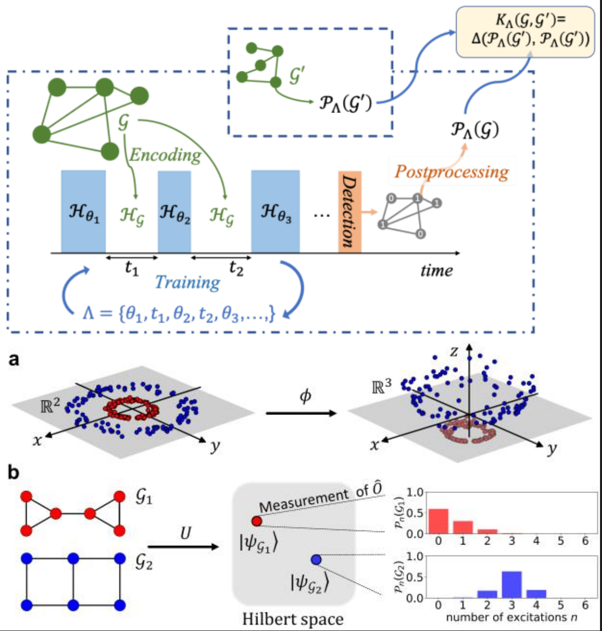


Staggered magnetisation histograms for 10 × 10 and 14 × 14 arrays, with MPS shown on the lower part of the 10 × 10 array (14 days for simulation with TeNPy).

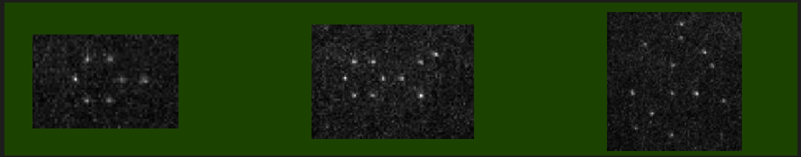
Application: Learning on Graph-structured data

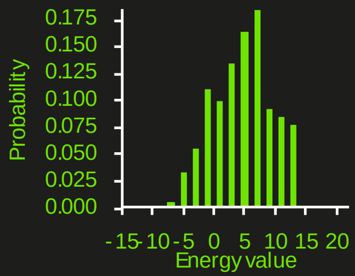
Graph Machine Learning offers a QML opportunity native to reprogrammable neutral atoms

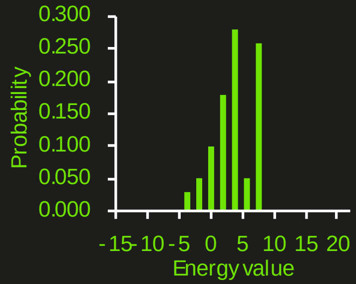
Neutral atom arrays enable ‘native’ implementations of graph machine learning techniques



Quantum procedures go beyond classical means. Geometry induced by the quantum procedure cannot be efficiently reproduced by classical means







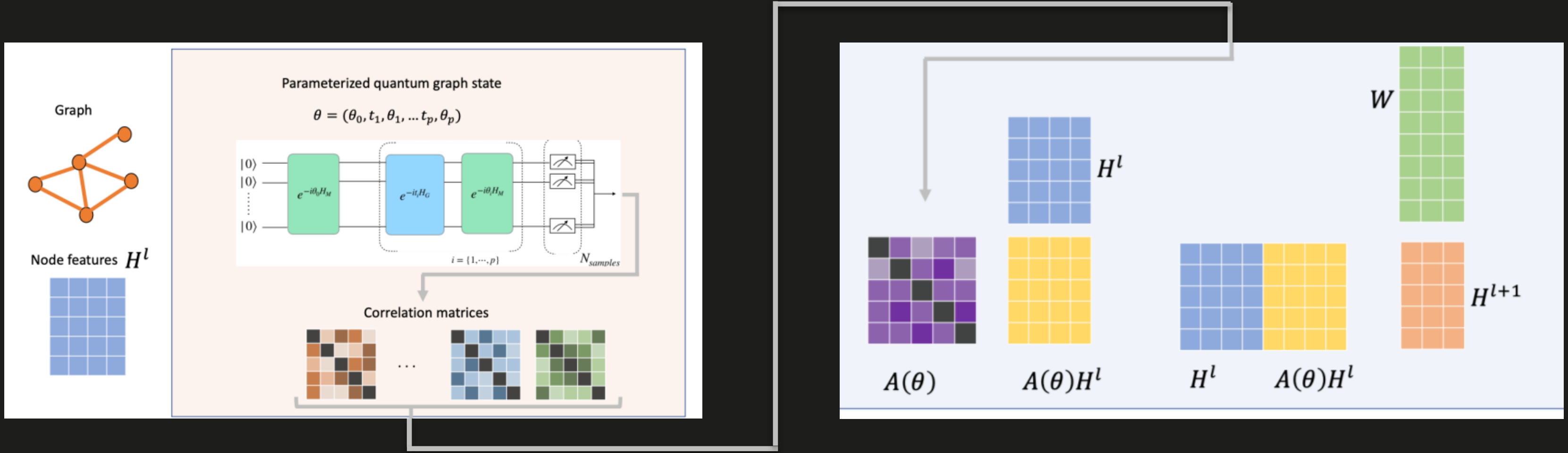
Source: Work in Progress + “Quantum evolution kernel : Machine learning on graphs with programmable arrays of qubits”, Louis-Paul Henry, Slimane Thabet, Constantin Dalyac, Loïc Henriet, Phys. Rev. A 104, 032416 (2021)

Application: Enhancing classical graph ML with quantum features

Graph Machine Learning could benefit from quantum correlations[1]

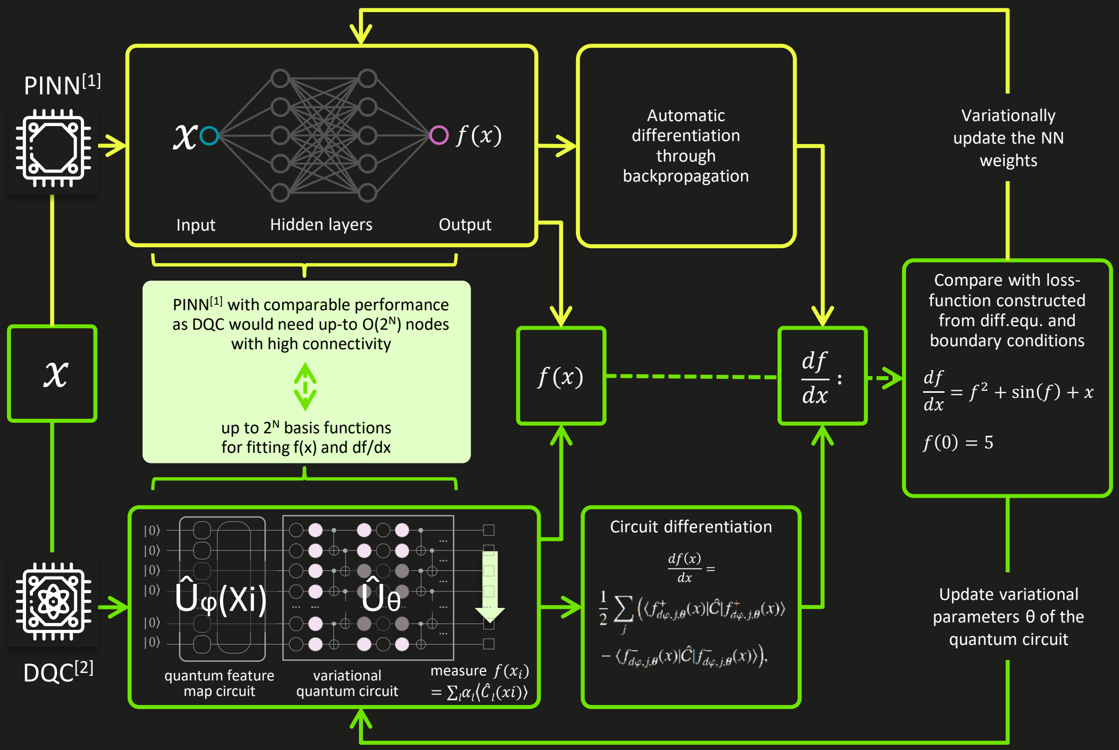
Quantum Graph Feature maps encode graph into Hilbert space and correlation matrices are observed

Aggregation weights are computed using the long-range correlations of a quantum system



[1] "Extending Graph Transformers with Quantum Computed Aggregation", Slimane Thabet, Romain Fouilland, Loic Henriet, https://arxiv.org/abs/2210.10610 (2022)

Application: Solving Non-Linear Partial Differential Equations



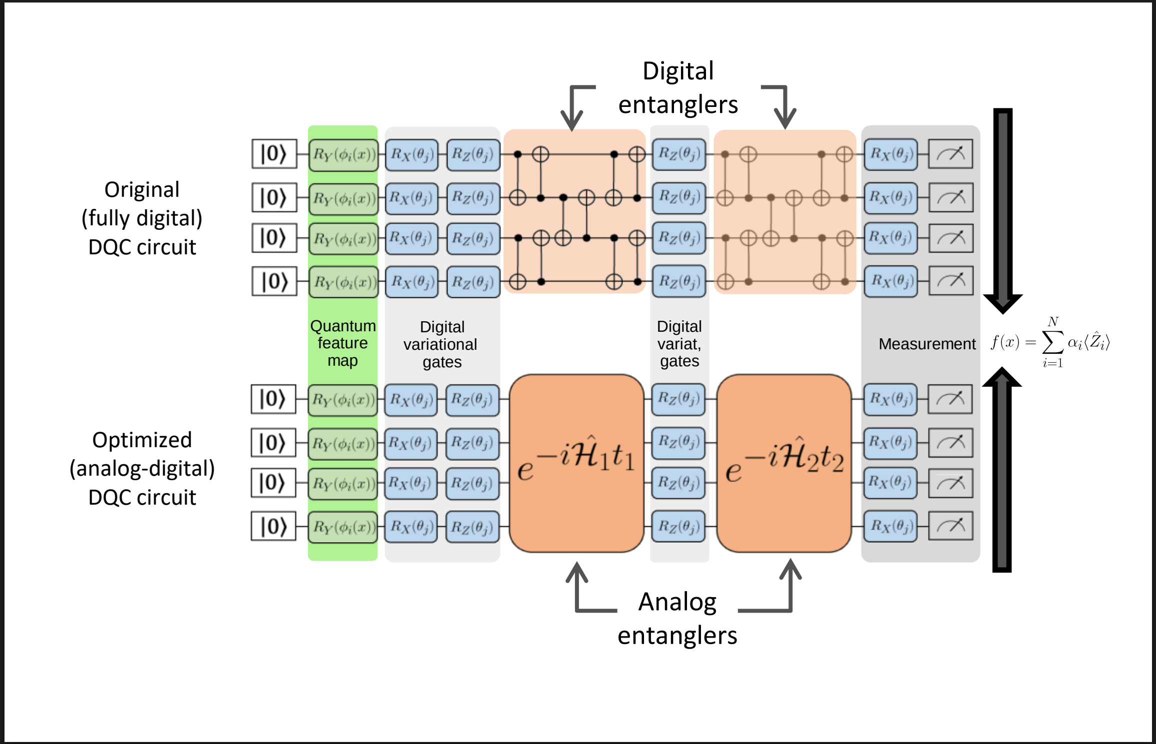
DQC

- DQC is a variational approach, where parametric functions are represented by measurements on the output of quantum circuits
- The upper part describes the structure of a classical neural network, while the lower part describes the structure of DQC
- The neural network is essentially a non-linear function generator which, given an input x, produces an output f(x). One trains the NN to represent the function that solves a DE given boundary conditions. At a given step, a loss function is evaluated and an update of the NN weights is decided in order to improve the quality of the output. One very important ingredient here is automatic differentiation, which allows you to not only have access to f, but also to the derivative of f with respect to x
- What we proposed for DQC is to use a quantum circuit to produce a universal function generator, similar to the classical case, sometimes also called a Quantum Neural Network or Quantum Model
- The analogue of the NN consists of a quantum circuit. Very much like automatic differentiation for classical neural networks, there are ways to access function derivatives through analytical circuit differentiation

[1] Solving nonlinear differential equations with differentiable quantum circuits https://arxiv.org/abs/2011.103955 Phys. Rev. A 103, 052416 (2021)

Digital / Analog setups provide a promising solution for DQC implementation

Digital / Analog Quantum Computation

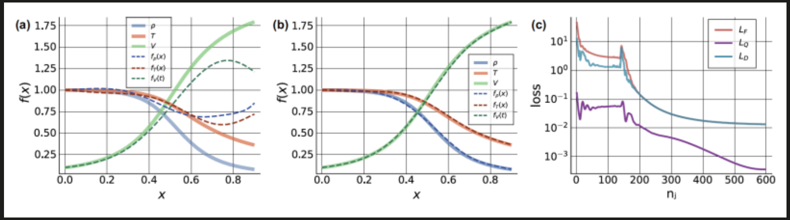


- **Digital**: algorithm implemented through sequence of **discrete** quantum gate operations
- **Analog**: user has control over small number of parameters and the quantum computer evolves towards an answer **continuously**[2]
- Digital is **universal**, but noise limits the use to **very short gate sequences**, which limits the near-term potential for quantum advantage
- Analog is perhaps **not fully universal**, but researchers are finding that it requires typically **10^4-10^5 less quantum operations**
- Analog quantum (or analog-digital) may therefore very well be our best chance **to implement DQC workflows**

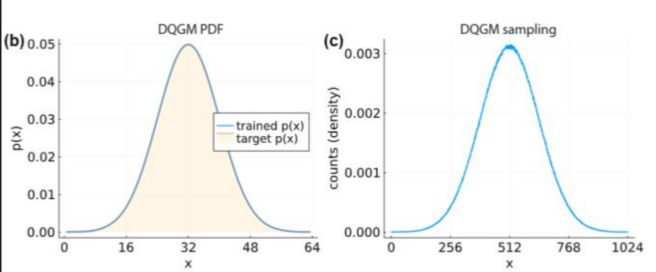
Application: Quantum (Scientific) Machine Learning (QSciML)

QML with Digital-Analog QNN circuits for simulating systems governed by Differential Equations

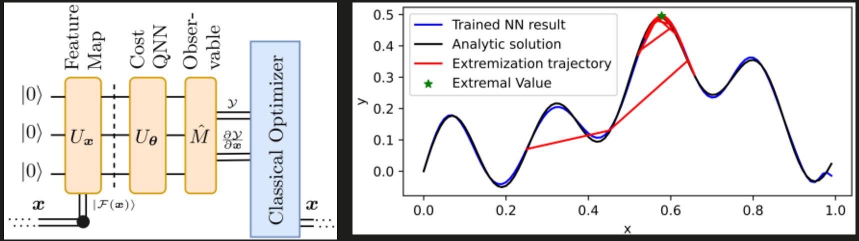
Solving known deterministic equations (PDE)



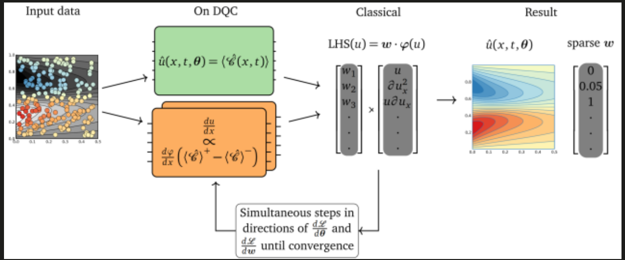
Differential Constraints Help Train Generative models



Optimizing control/model parameters to maximize solution characteristics of merit



Learning DE-models based on real-world data



[1] Solving nonlinear differential equations with differentiable quantum circuits https://arxiv.org/abs/2011.103955 Phys. Rev. A 103, 052416 (2021)
[2] Protocols for Trainable and Differentiable Quantum Generative Modelling https://arxiv.org/abs/2202.08253
[3] Quantum Extremal Learning https://arxiv.org/abs/2205.02807
[4] Quantum Model Discovery https://arxiv.org/abs/2111.063766

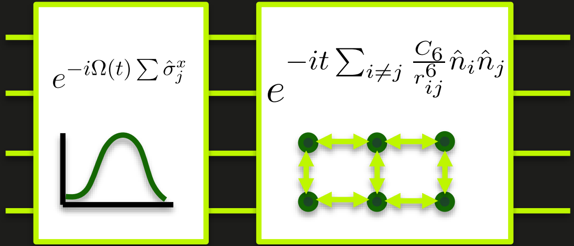
From Analog applications to Digital-Analog paradigms

Pulse-level Control Paradigms

Analog

With “Analog” quantum computing, we mean continuous control of our system Hamiltonian by the application of optical addressing with laser light
As an example, we can operate our quantum optical system in the Ising model regime, where the parametric Hamiltonian can be described as

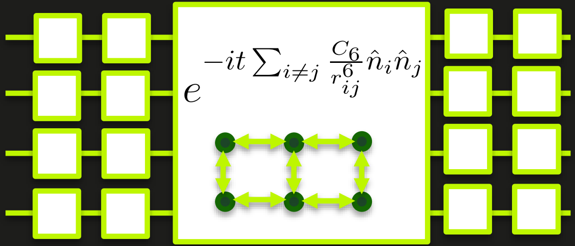
$$\mathcal{H}(t) = \frac{\hbar}{2}\sum_j \left[\Omega_j(t)\hat{\sigma}_j^x - \hbar\sigma_j\delta_j(t)\hat{n}_j\right] + \sum_{i\neq j}\frac{C_6}{r_{ij}^6}\hat{n}_i\hat{n}_j$$



Digital-Analog

In a “digital-analog” paradigm, we define it as digital operations, such as arbitrary single-qubit gate(s)/rotations, interleaved with global multi-qubit operations such as evolution over an Ising Hamiltonian.

This allows efficient entanglement at low circuit depth, while simultaneously allowing more specific control of individual rotations



Where to go next in QML? What challenges are to be tackled?

Pulse-level Control Paradigms

(Analog) circuit differentiation is too expensive! How can we do practical gradient descent?

- We, as part of a broader community on the topic, have also developed extensions of the parameter shift rule towards more general unitaries including analog blocks
- Recent work has expanded further on these, including explicity formulations for analog evolutions.
- However, for optimization based on gradient descent, the cost compared to backpropagation is simply too high to be practical

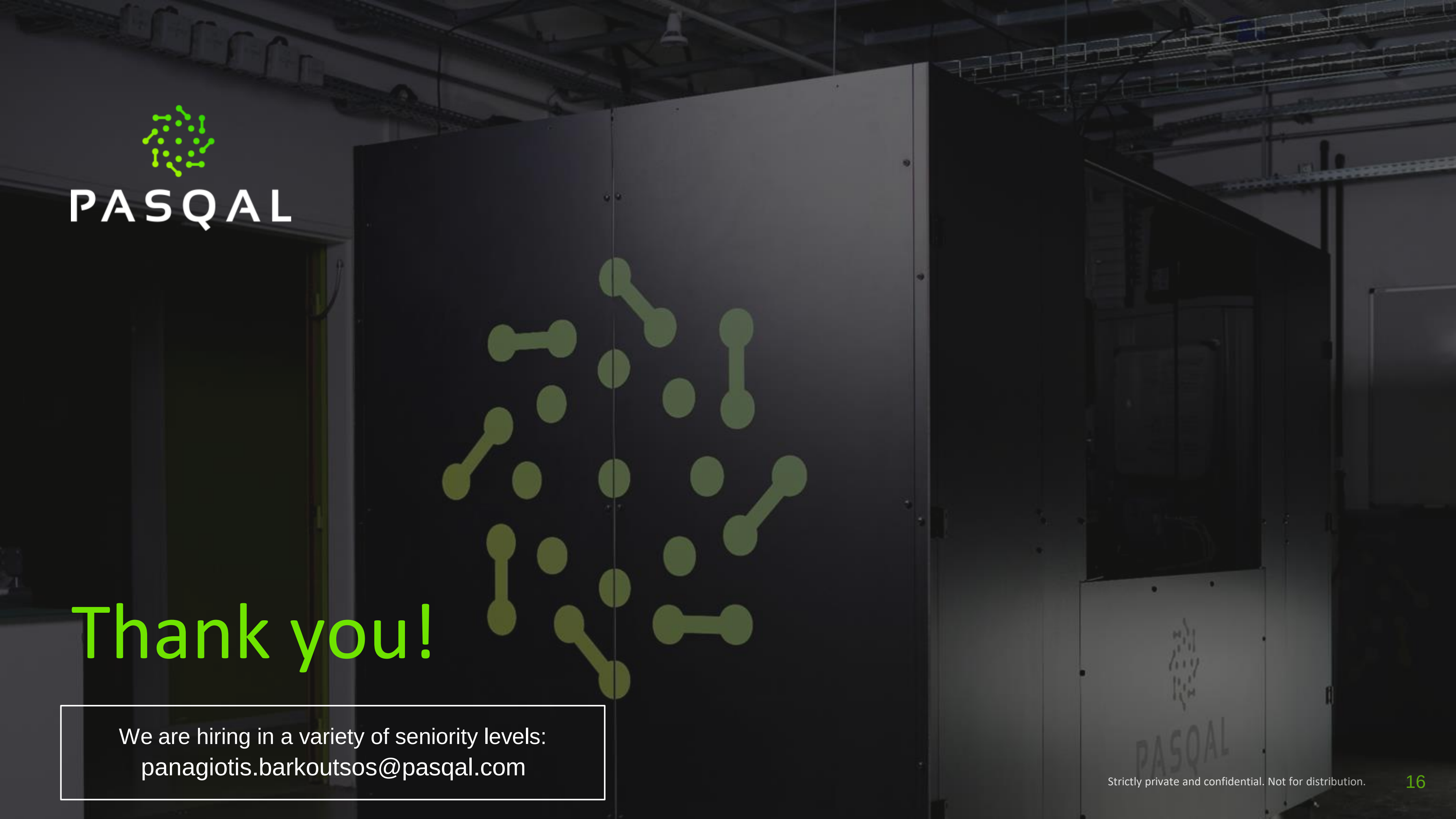
Open questions

- Can we train classically?
- Can we train more cheaply? Stochastic?

Quantum Advantage of Quantum Neural Networks over classical (Deep) Neural Networks?

- Several papers which use expressivity arguments to claim a theoretic advantage over classical
- Classical neural networks were only very recently understood more rigorously theoretically – is it simply too early to expect the same here? Do we need a quantum computer to understand a quantum computer?
- Several papers pointing out limitations of QNN and QML in general, but often it is not clear how broadly applicable the statements are, and no clear solutions exist yet

[1] Generalized quantum circuit differentiation rules https://arxiv.org/abs/2108.01218 Phys. Rev. A 104, 052417 (2021)



PASQAL

Thank you!

We are hiring in a variety of seniority levels:
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